Characterizing the Effects of Mutual Coupling on the Performance of a Miniaturized GPS Adaptive Antenna Array

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BIOGRAPHY

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ABSTRACT

This paper describes the design of a compact, M-code capable, four element GPS adaptive antenna arrays made from stacked patch microstrip antenna elements. Possible applications for these antenna arrays are in military airborne platforms where the space available for installing antennas is very limited. To meet future GPS M code requirements, the antenna elements were designed for a bandwidth of 24 MHz. The size of the entire array assembly including the metal ground plane on which it is mounted is 4.625"; the size of the array itself is even smaller - only 3.5" square. The array also has a low profile with a height of just 1.2" including the radome cover. The size of the microstrip antenna elements has been reduced in size to fit within this aperture by using high dielectric constant substrate materials. The technical challenges in the design was to reconcile conflicting requirements imposed by the small antenna size and the wider 24 MHz bandwidth demanded by the M-code. Each element in the array fed by a self-diplexing feed consisting of coaxial probes connected to surface mount quadrature hybrids for circular polarization. Satisfactory M–code performance of the antenna array has been demonstrated by measuring the signal fidelity of the correlation peak using an M-code transmitter, down-converter and receiver built at MITRE. The results of mutual coupling measurements on this circularly polarized array are described with their impact on array design. The antenna patterns and other pertinent performance characteristics of this array are being measured. These results will be described in a future paper.

INTRODUCTION

Space limitations in some military airborne platforms dictate the need for compact, low profile, multiple-element GPS adaptive antenna arrays for combating interference. With the modernisation of GPS, future military systems will be required to support the new M-code signal at both L_1 and L_2. This requires that the bandwidth of the antenna elements in the array be increased to 24 MHz from the current 20 MHz required for P(Y) code. The dual-sideband M-code structure also puts emphasis on good antenna performance at the edges of the band. This paper describes the design of compact four-element microstrip adaptive antenna arrays capable of meeting the M-code performance requirements at both L_1 and L_2. A microstrip antenna element was selected for building this array because of its low profile, small size and low manufacturing cost. The difficulty in building such an antenna array arises from simultaneously trying to meet two opposing design requirements, namely reduced antenna size and wider bandwidth required for the M-code. A reduction in the size of a microstrip antenna element so as to fit within this small array can only be achieved by using a high dielectric constant substrate material. However, since this increases the Q factor of the antenna it can be detrimental to the operational bandwidth and may preclude efficient reception of the M-code signal. A reduction in the size of the array also brings the antenna elements closer together causing an increase in mutual coupling, which can also affect the performance of the array. The challenge to the antenna designer is in balancing these opposing design requirements to achieve an optimised design that best meets the desired performance objectives. The dimensions of the four element antenna array described in this paper is just 4.625" square, including the supporting ground plane on which the four antenna elements are mounted; this may be small enough for many of the military airborne platforms where space is at a premium. The height of the array, including its radome cover, is 1.2" to meet aerodynamic requirements. To reduce cost, the microstrip antenna elements in the array were built from commercially available copper clad dielectric substrate material that lends itself to printed circuit technology. Two arrays have been built and tested to fit within this 4.625" square aperture using two different types of dielectric substrate materials. Satisfactory M-code performance of this array in both the L_1 and the L_2 bands has been demonstrated by measuring the signal fidelity of the M-code correlation function; an M-code modulator for the BOC (10, 5) waveform and its corresponding receiver built at MITRE were used in these tests. The VSWR and mutual coupling between the elements of this array have been measured at both of the GPS frequency bands and will be discussed in this paper. Other performance characteristics of the array such as antenna patterns and nulling performance are currently being measured. They will be described in a future paper.

DESIGN OF THE FOUR ELEMENT ANTENNA ARRAYS

Selection of Dielectric Substrate

The dielectric substrate material selected for this antenna array has to have dielectric constant that is high enough to allow sufficient reduction in the size of the patch antenna so as to make four elements fit within the 3.5" square array aperture (excluding the bottom ground plane supporting the array); they must also be easy to machine and etch to reduce the cost and complexity of building the array. Since the antenna array is intended for airborne applications it has operate over a wide range of external temperatures, hence, temperature stability of the dielectric constant is also an important parameter in the selection to avoid de-tuning of the antenna element caused by changes in the temperature of the operational environment.

Although several ceramic substrates with high dielectric constants are currently available, they were not selected for making this array since they need special diamond tipped tools for cutting and drilling and also need special sputtering equipment or thick film deposition techniques to apply copper cladding to their surface for making the patch antenna elements We have selected instead two types of commercially available dielectric substrate material made by the Roger's Corporation – these are: 1) 6010 LM with a dielectric constant of 10.2 and a loss tangent of 0.002 and 2) TMM13i with a dielectric constant of 12.78 and a loss tangent of 0.002. These dielectric substrates are made from a combination of high dielectric constant ceramic blended into a lower dielectric constant material; they have the highest dielectric constant of any commercially available substrate material, other than pure ceramics, for making these antennas; both materials come with copper cladding and are relatively easy to machine and etch thereby reducing the cost and complexity of building the array. 6010 LM has low moisture absorption properties; whereas TMM13i is a temperature stable microwave substrate material whose variation of dielectric constant with temperature is lower than 6010LM. The dielectric constant of both of these materials is high enough to achieve sufficient reduction in the size of the antenna elements to fit within the footprint of the array. TMM13i being the higher dielectric material allows for smaller size antenna elements allowing more air gap separation between antenna elements; our tests also show it has better performance overall.

Antenna Element Design

A picture of the two four element arrays that were built is shown in Figure 1.

The dielectric substrate for the array shown on the left was 6010LM; the substrate used for the array on the right was TMM 13i; both of these substrates were made by the Roger's Corporation. Each of the four-antenna element in these arrays is a pair of square, stacked microstrip patches; the top patch operates in the L_1 band and the bottom patch at L_2. Each antenna element in the array was mounted on its own discrete dielectric puck to reduce mutual coupling between the array elements caused by surface waves propagating through the substrate; the finite size of the dielectric puck also improves the bandwidth of the microstrip antenna element. The top and bottom patches were fed by individual pairs of miniaturised coaxial probes located at orthogonal positions within each patch. The location of the two probes in each patch was optimised to yield an input impedance at resonance that was close to 50 ohms at the center frequency of each GPS frequency band. This design expedient allows both the top and bottom patch antenna elements to meet a return loss of –10 dB (VSWR of 2:1) at the edges of the 24 MHz band to ensure minimum distortion of the M-code modulation waveform. Right Hand Circular Polarization in each element was obtained by connecting each pair of coaxial cables to a compact and broad band "Xinger" surface mount quadrature hybrid made by ANAREN. The antenna element is "self diplexing" and does not need an external diplexer to separate out the L_1 and L_2 frequency bands.

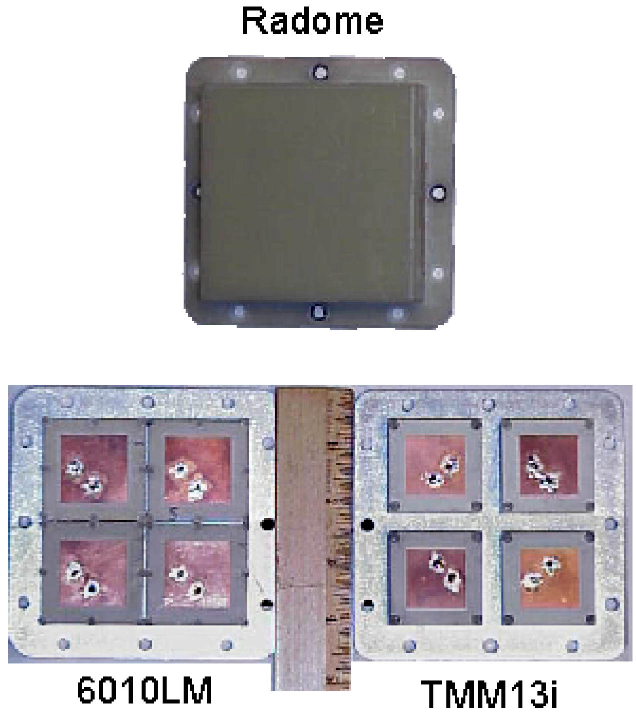


Figure 1. Picture of the GPS Miniaturized Four-Element Adaptive Arrays Using 6010 LM Substrate (Array on Left) and TMM13i Substrate (Array on Right)

Electrically thick substrates were used to improve both the bandwidth and the efficiency of the antenna elements. The total thickness of the substrate used in the 6010LM array was 0.400," consisting of two layers, each 0.2" in thick, and one for each patch antenna. The total thickness of the TMM13i array was 0.6" in thickness, consisting three layers each 0.2" thick; of these one layer was used as the substrate for the top patch and two for the bottom patch. The bottom patch needed a thicker substrate to improve its bandwidth. The size of the dielectric puck supporting the patch antenna elements was 1.7125" square for the 6010LM substrate and 1.56" square for the TMM13i substrate. In the four-element array made from the TMM13i substrate, the separation distance between the elements was 1.9" or 0.253 wavelength at the center frequency of the L_1 band and 0.197 wavelength at the center frequency of the L_2 band. The separation distance was approximately the same for the array built from the 6010LM substrate material.

The resonant frequency of each antenna element in the array environment is affected by three factors which complicates the optimum design of this array:

- Mutual coupling between antenna elements, because of the close inter-element spacing, has a significant impact on the resonance frequency of both the top and bottom antenna patch elements; mutual coupling affects the top and bottom patches differently because of the difference in their physical locations and frequency.

- The proximity of the radome to the antenna also impacts the resonance frequency. Since the top patch is closer to the radome surface it can act as a "superstrate" layer for this antenna element; the bottom patch is less sensitive to the presence of the radome since it is buffered by the intervening substrate layers.

- The finite size of the supporting dielectric puck makes the antenna elements used in this array different from a conventional microstrip patch antenna with a large (ideally infinite) dielectric substrate. In fact, this array element can considered to be a hybrid between a dielectric resonator antenna and a microstrip patch antenna. Although this type of antenna configuration can be analysed by using a Transmission Line Matrix (TLM) code such as "MICRO-STRIPES" [1] that is currently available at MITRE, the computational complexity and the run times needed to analyse and optimise a full four element antenna array, including the effects of mutual coupling and a radome, will be prohibitively difficult, time consuming and expensive.

The design procedure that was used to tune the antenna elements to the desired frequency was to first calculate approximate dimensions of both the top and bottom patch elements of an isolated element (with no other antenna elements in its vicinity) using commercially available software such as ANSOFT ENSEMBLE [2] or by other alternate microstrip antenna design software available at MITRE. All four-antenna elements were then mounted at their respective locations in the array and the radome cover was placed over the entire array. The dimensions of both the top and bottom patch of each antenna element was then tuned in an iterative manner to get the correct resonance; this tuning procedure takes into account the mutual coupling between elements, the presence of the radome and the finite size of the dielectric substrate. The results achieved by tuning the antenna elements of the array using this procedure are shown in Figures 2 and 3; these figures show the measured return loss over a 24 MHz band at both L_1 and at L_2 respectively for each of the two excitation probes on all four elements of the array built with the TMM13i, the substrate with the higher dielectric constant.

Notice that six of these probes have a return loss of less than –10 dB (VSWR of 2:1) and two have return losses less than –9 dB (VSWR of 2.1:1). The VSWR for the other array elements built with the 6010LM substrate was equally good with all elements showing a return loss of less than –10 dB.

Figure 4 shows the group delay for one of the antenna elements in the array measured across the 24 MHz band at L_1 as a function of elevation the elevation angle ranging from 0^0 to $+90^0$. The maximum variation in group delay is less than 6 nanoseconds.

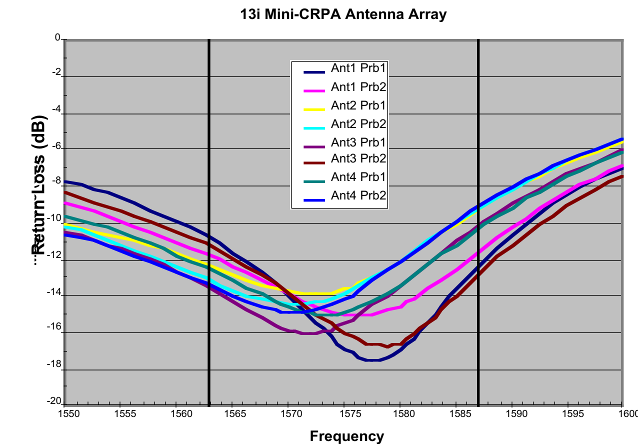


Figure 2. Measured Return Loss in the GPS L_1 Band of Excitation Probes for the Four Elements of the Miniaturized GPS Adaptive Antenna Array Made From TMM13i Substrate Material

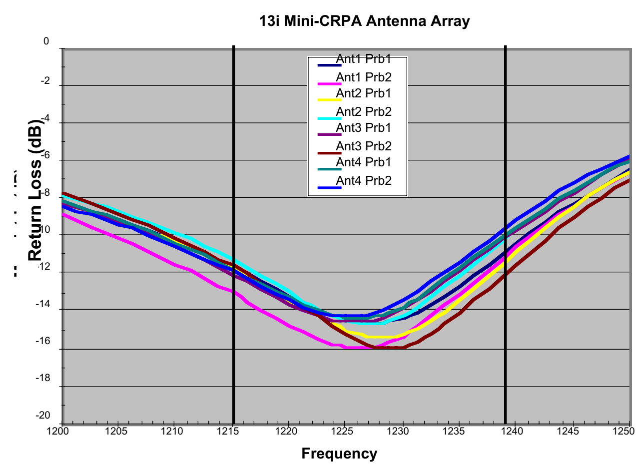
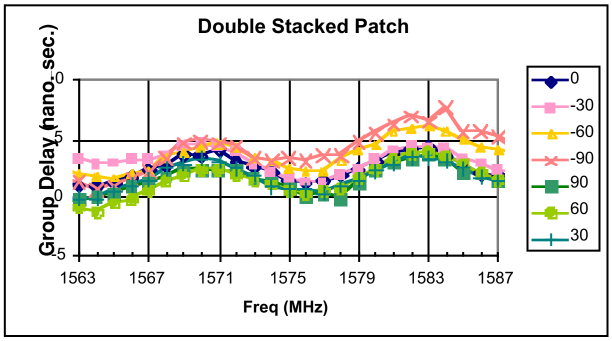


Figure 3. Measured Return Loss in the GPS L_2 Band of Excitation Probes for the Four Elements of the Miniaturized GPS Adaptive Antenna Array Made From TMM13i Substrate Material



Group Delay

Figure 4. Measured Group Delay as a Function of Elevation Angle for an Antenna Element in the Four-Element Adaptive Array Made From 6010LM Substrate Material

M-CODE CORRELATION MEASUREMENTS WITH THE ARRAY

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Satisfactory M-code performance of all four elements of the two arrays was also demonstrated by measuring the signal fidelity of the correlation. These measurements were made using two different techniques. In the first method an M-code modulator and its corresponding receiver, both built at MITRE, were used in the tests. Figure 5 shows a picture of this M-code receiver. The transmit antenna was a L band helical antenna, 26" long and about 2.8" in diameter with good return loss and gain across both the

Figure 5. Picture of the MITRE M–Code Receiver

GPS L_1 and the L_2 frequency bands. A picture of the helical antenna is shown in Figure 6. In the second method used for measuring the correlation, the signal from the receive antenna under test was down-converted to 70 MHz at both the GPS L_1 and L_2 bands using a connectorized down converter built at MITRE; the 70 MHz signal was then analysed using a Celerity 2010 DSP unit to generate the correlation. The M-code correlation measured by both methods was very similar. Figure 7 shows a block diagram of the data acquisition system used for these measurements.

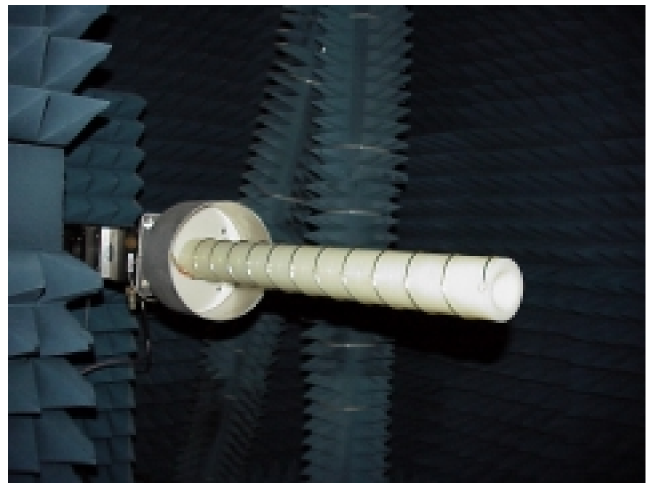

Figure 6. Picture of Helix Transmit Antenna Used for M-Code Correlation Measurements on Array Elements

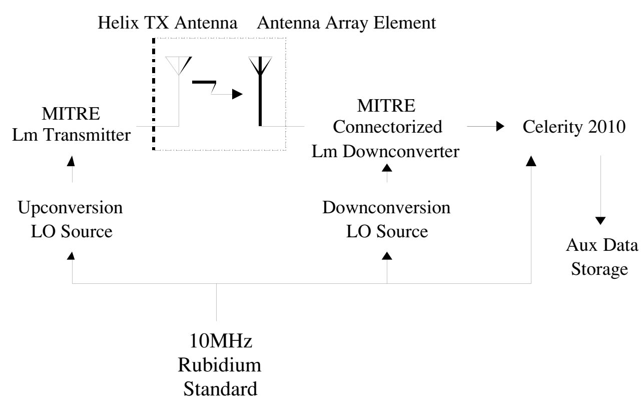

Figure 7. Block Diagram of the Data Acquisition System for M-Code Correlation Measurements on an Antenna Element in the Four Element Adaptive Array

Figure 8 shows the measured correlation peak of the BOC(10, 5) code waveform in the L_1 band for Element #1 of the four element array built with the TMM13i substrate material; the other three elements of the array were terminated in matched loads during these measurements.

The BOC(10,5) modulation selected for the M-code signal for this experiment has a sub-carrier frequency f_S =

10.23 MHz and a spreading code rate f_C = 5.115 MHz. The figure shown at the top is the measured correlation peak when the modulated transmit signal is connected directly to the receiver through a coaxial cable – this can be considered as the "ideal" shape of the M-code correlation peak in the absence of any distortion generated by either the transmit or receive antennas. The Y axis in this figure is the normalized magnitude of the correlator output squared; the X axis is the delay in nanoseconds. Notice that there is there is little signal energy after ± 195.5 nanoseconds, which corresponds to the chip length (or inverse of the spreading code rate). It can, therefore, be used as the "reference waveform" to gauge the distortion caused by the transmit and receive antennas. The bottom figure in Figure 8 shows the measured correlation peak after reception by element #1 of the array. A comparison of the top and bottom figures shows that this antenna element in the array causes negligible distortion in the signal fidelity of the correlation peak. The only visible sign of distortion is that the magnitude of the first sidelobe on the right hand side has increased slightly over that observed in the reference. Figure 9 shows the corresponding correlation peaks for the reference and antenna element #1 measured in the L_2 band.

Once again the comparison of the top and bottom figures show little to no distortion caused by this antenna element. Similar measurements were made for the other three antenna elements in this array and also for all four elements in the second array made from the Rogers' 6010 LM substrate material. The results of these measurements show that both of the four element arrays that have been built have sufficient bandwidth to track the M-code signal with little if any signal distortion.

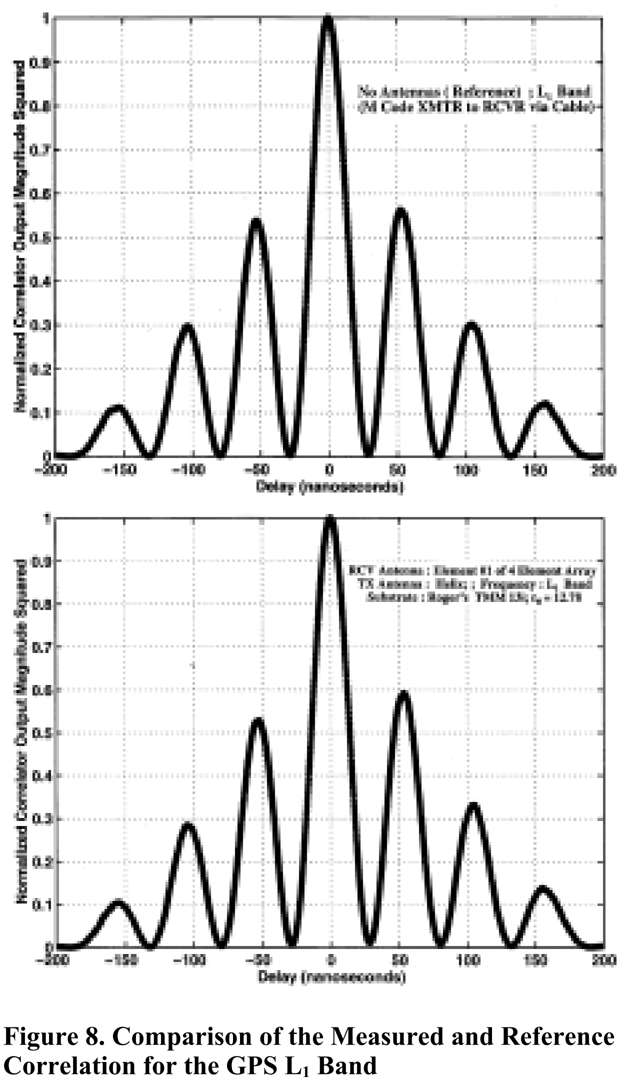

Figure 8. Comparison of the Measured and Reference Correlation for the GPS L_1 Band

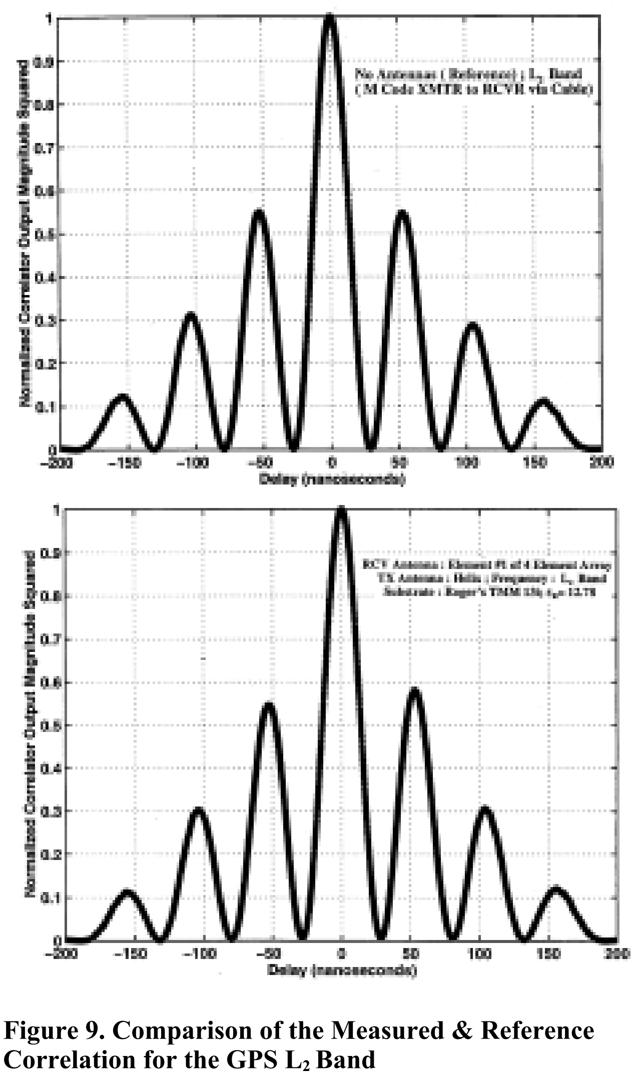

Figure 9. Comparison of the Measured & Reference Correlation for the GPS L_2 Band

MEASURED MUTUAL COUPLING BETWEEN ANTENNA ELEMENTS

The E and H plane mutual coupling between the square microstrip antenna elements used in the array is dependant on the separation distance between the edges of the microstrip antenna elements, the dielectric constant of the substrate material and the thickness of the substrate. Mutual coupling in the H plane is much greater than in the E plan for antenna array elements made with a high dielectric constant substrate such as 6010LM or TMM13i and with edge separation distances that are closer than 0.3 wavelength [3]. Mutual coupling affects the resonance frequency of the antenna elements in the array and needs to be taken into account while tuning the elements to resonance at the desired frequency; this was compensated by tuning each antenna element at its proper location within the array environment as explained earlier in this paper. Mutual coupling can also affect the circular polarization axial ratio of the antenna especially when there is strong cross polarized coupling (RHCP to LHCP) between the array elements as in this array.

The mutual coupling between the four elements in the array made from the 6010LM substrate material were measured to determine both the principal polarization coupling (RHCP to RHCP) as well as the cross polarization coupling (RHCP to LHCP) for all four elements in the array. Figure 10 shows a layout of the array showing the numbers used for identifying each element in the array to assist in measured results shown in the figures that follow. The probe locations for L_1 are shown by the

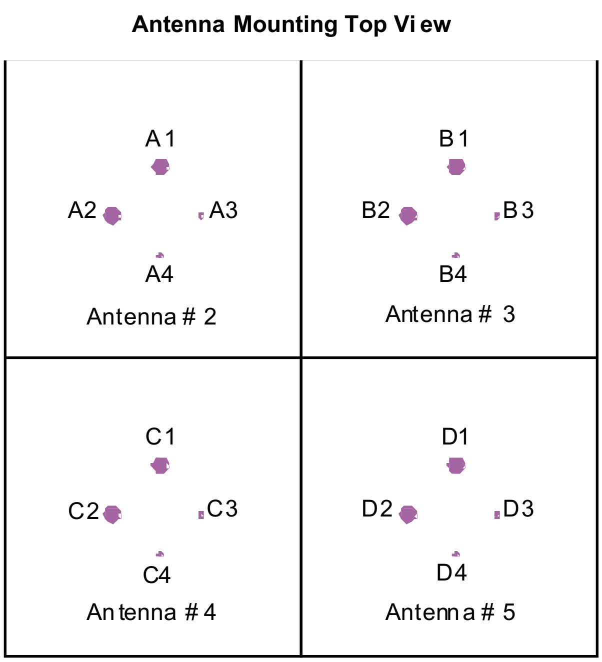

Figure 10. Diagram of Probe Locations on Array Antenna Elements for Mutual Coupling Measurements

large circles (e.g., by A_1 and A_2 in Antenna No. 2) and the corresponding probe locations for L_2 excitation are shown by the smaller circles (e.g., A_3 and A_4 in Antenna No. 2).

In Figure 11 the figure at the left shows the magnitude of the measured RHCP to RHCP coupling between the two top adjacent elements 2 and 3 in the array (shown in blue) and also the two bottom adjacent elements 4 and 5 (shown in red.) in the GPS L_1 band The figure shown on the right of Figure 11 is the coupling between the adjacent top and bottom elements – 2 to 4 and 3 to 5. Notice that the coupling for all these cases is about –11 dB and is uniform across the band.

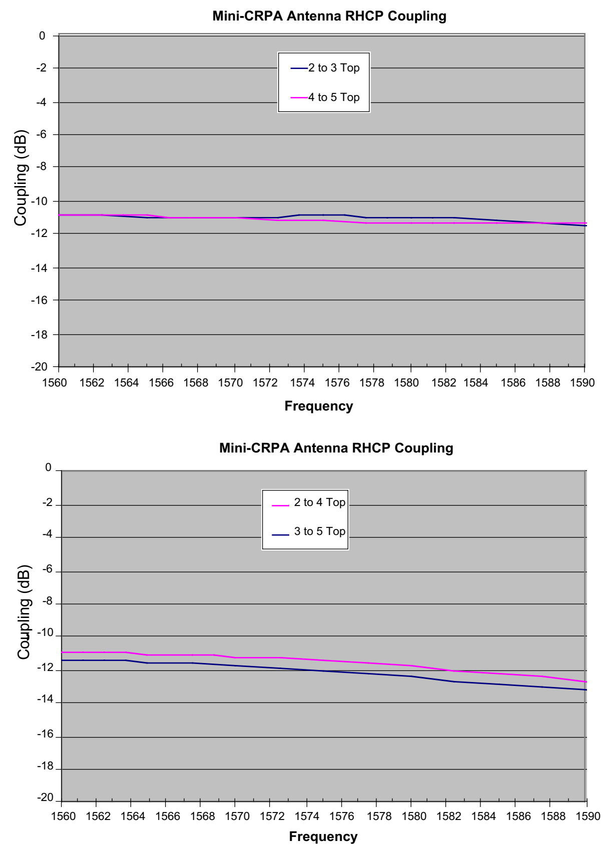

Figure 11. Measured Mutual Coupling for Principal Polarization (RHCP to RHCP) Between Adjacent Elements in Four-Element Array

The data shown in Figure 12 is the measured cross polarized coupling (RHCP to LHCP) between these elements in the GPS L_1 band. The figure on the left shows the measured RHCP to LHCP coupling for the top two adjacent elements 2 and 3 (shown in blue) and between the bottom two adjacent elements 4 and 5 (shown in red). The figure shown at the left is the cross polarized coupling between elements 2 and 4 – the top and bottom elements on the left of the array and between 3 and 5 – the top and

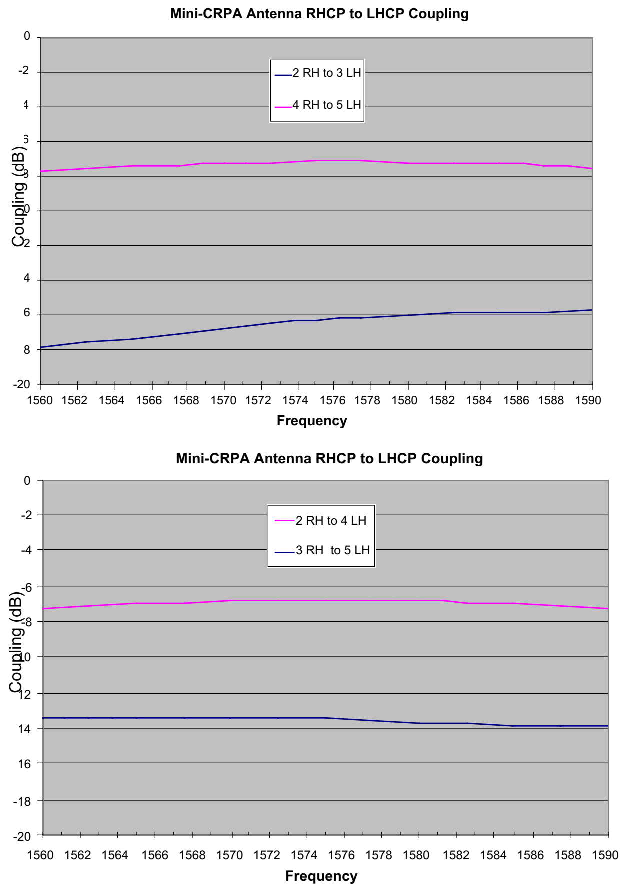

Figure 12. Measured Mutual Coupling for Cross Polarization (RHCP to LHCP) Between Adjacent Elements in Four-Element Array

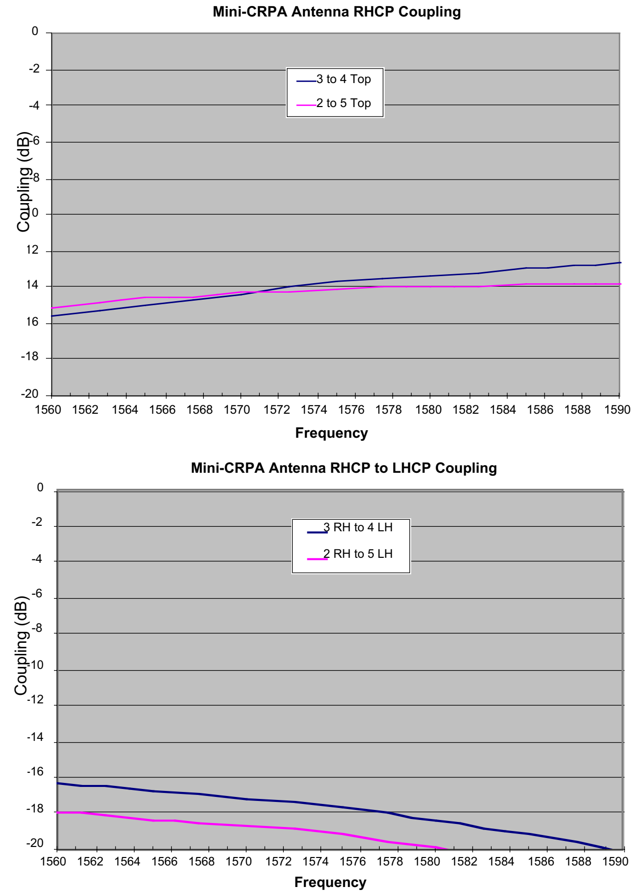

Figure 13. Measured Mutual Coupling for Between Diagonal Elements in Four-Element Array (Principal and Cross Polarization Coupling)

bottom elements on the right of the array. A comparison of these results shows coupling as strong as –8 dB for some antenna elements and only –13 dB for others. This disparity in coupling can cause significant changes in the axial ratio of the fields radiated by these antenna elements; the explanation for these polarization coupling anomalies can be explained by examining the linear polarization coupling between the various probes used to excite the antenna elements. Figure shows the measured mutual coupling between diagonally located elements in the array – coupling between elements 2 to 5 (shown in red) and also between elements 3 to 4 (shown in blue). The figure shown on the left is the principal polarization coupling (RHCP to RHCP), whereas the one at the right is the cross polarization coupling (RHCP to LHCP). Notice this coupling is much less than shown in the previous two figures; principal polarization coupling varies between –12 and –16dB and the cross polarized coupling between –16 and –20 dB.

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